Laboratory Evaluation of a Manure Additive for Mitigating Gas and Odor Releases from Layer Hen Manure

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Abstract

Manure additives are widely used to mitigate gas and odor emissions from manure or improve manure properties. However, the reported effectiveness of some manure additive products has been mixed and most of the studies on poultry manure have been on chemical additives. A laboratory study was conducted to evaluate an enzyme-based commercial manure additive for its potential reductions of ammonia (NH_3), carbon dioxide (CO_2), hydrogen sulfide (H_2S), and odor releases from layer hen manure. Eight 122-cm tall and 38-cm diameter reactors, four treated with the additive and four control, were studied for 38 days with manure from commercial layer hen houses. The reactors were initially filled with 66-cm height manure followed by weekly additions of 5 cm each. Ventilation air was supplied to the reactor headspace to simulate winter ventilation rates in layer hen houses. Concentrations of NH_3, CO_2, and H_2S in the reactor exhaust air were measured with gas analyzers for 10 min, six times daily. Odor intensity was assessed by a trained odor panel. Open-headspace tests were also conducted to corroborate the observations in the reactor study. Study results showed that the average 4-reactor group mean release rates ± standard deviations of NH_3 were 17.3 ± 15.1 and 19.9 ± 13.4 $\mu g\ s^{-1}$ from the control and treated groups, respectively. Those of CO_2 were 1086 ± 157 $\mu g\ s^{-1}$ from the control and 1146 ± 237 $\mu g\ s^{-1}$ from the treated groups. Release of H_2S from the reactors could not be detected. The odor intensities were 3.5 ± 0.3 and 3.4 ± 0.3 before and after the additive spray, respectively. Application of the additive onto the manure did not demonstrate effect on the releases of NH_3 ($P > 0.41$), CO_2 ($P > 0.21$), and odor ($P > 0.71$) from the manure.

Keywords: Agricultural wastes; Emission mitigation; Manure treatment; Poultry manure; Waste management.

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INTRODUCTION

Modern livestock and poultry production facilities are becoming larger and more concentrated, resulting in greater public scrutiny and stricter government regulations. Emissions of certain aerial pollutants, especially ammonia (NH_3), and odors from poultry facilities have been an ecological and environmental concern. Average NH_3 emission rates from high-rise layer hen houses range from 0.60 to 1.28 g d^{-1} hen^{-1} at various locations in the U.S. (Heber et al., 2005; Liang et al., 2005; Lin et al., 2012; Wang-Li et al., 2013). Odor emissions from layer hens were 59.3 OU_E s^{-1} AU^{-1} (OU_E = European odor unit; AU = Animal unit or 500 kg live mass) from two high-rise houses in Indiana (Heber et al., 2005) and 46.7 OU_E s^{-1} AU^{-1} from two manure-belt houses in Ohio (Zhao et al., 2015).

Manure additives are widely used in livestock and poultry farms. Commercial manure additives are claimed to reduce NH_3 and hydrogen sulfide (H_2S) emissions, combat odors and/or odor production, break down solids, and increase the availability of manure nutrients. In the U.S., manure additives were introduced as early as in the 1910s. For example, acid phosphate was recommended to preserve nutrients in poultry manure by the Maine Agricultural Experiment Station (Pearl, 1913). There are currently about 50 commercial proprietary additive products available in the U.S., in addition to general chemicals such as aluminum sulfate and aluminum chloride. These additives come in a variety of forms including chemicals, bacteria, enzymes, and other biological products. Investigations have been conducted on different additives and reports published with mixed results. The largest laboratory study of manure additives so far was an evaluation of 35 commercial manure additives for controlling odor, NH_3, and H_2S releases from swine manure in three consecutive 42-d trials. Results showed that, at 95% certainty, only 23% of the products reduced NH_3, 20% of the products reduced H_2S, and no products reduced odor (Tengman et al., 2001). Another study of three additives in swine manure showed only very limited odor and solids reductions (Stinson et al., 2000). Based on different research results, Lorimor et al. (2002) concluded that manure additives are generally not reliable for emission controls. However, a couple of more recent studies demonstrated that some additives showed improvement in air quality (Shah et al., 2007) and odor reduction (Brandt et al., 2016).

Although testing of additives to reduce NH_3 and odor emission from chicken manure has been conducted since the early 1920s (e.g., Collison and Conn, 1922), relatively fewer studies on poultry manure were available in the literature (e.g., King et al., 2006; Tasistro et al., 2007) compared with those on swine manure (e.g., Yu et al., 1991; Alkanani et al., 1992; Li et al., 1998; Heber et al., 2000; Zhu et al., 2006). In addition, most of the studies on poultry manure evaluated chemical acidifiers to reduce ammonia emissions (e.g., Lim et al., 2008; Bejan et al., 2013).

A commercial manure additive Eco-Cure™ (Eco-Cure, Inc., Corte Madera, CA) has been in the U.S. market for more than a decade. It was advertised as an enzyme-based product for livestock and poultry producers to rapidly reduce NH_3 and odor releases upon contact with animal manure. In search for an air pollution abatement technology for layer hen houses to satisfy the abatement requirements of a Consent Decree with U.S. EPA (United States Environmental Protection Agency) (DOJ, 2004), an egg producer sponsored a laboratory study of this additive to determine its effectiveness on air pollution reduction. The producer desired a successful test to minimize the cost of reducing NH_3 emissions from their facilities; but the U.S. EPA demanded that preliminary data be collected before conducting the required field tests that could ultimately satisfy legal requirements. The U.S. EPA supervised the laboratory study to assure quality assurance and quality control. The objective of this paper is to report the effectiveness of Eco-Cure on reducing NH_3 and odor releases from stored layer hen manure under laboratory test conditions.

MATERIALS AND METHODS

Study design and laboratory facility

A 38-d study was designed to evaluate the additive with layer hen manure (Table 1). The manure was placed into eight vertical rigid PVC reactors, including four controls denoted as R-a to R-d and four treated denoted as R-e to R-h.

Table 1: Laboratory study schedule.

Study day	Manure operation/additive testing	Manure height*, cm	Analyzer calibration	Additive application
-1	Collection from layer hen house		√	
0	Filling and sampling**	66.0	√	√
7	Addition	71.1	√	√
14	Addition and odor evaluation	76.2	√	√
21	Addition and open-headspace test	81.3	√	√
28	Addition and open-headspace test	86.4	√	√
31		86.4	√	
35		86.4	√	√
37		86.4	√	
38	Sampling and emptying**		√	

Note: *Manure height was the distance from the reactor bottom to the manure surface; ** Samples were for manure analysis.

The reactors were 1.22 m tall and 0.38 m inside diameter with slip caps on each end. Each reactor was lined with 0.05-mm thick Tedlar® film on the top 64 cm of the inside walls and the "ceiling" of the reactor (inside the top slip cap) to create a chemically inert headspace (Figure 1).

The air inlet opening of the reactors was adjustable and telescoping to allow the inlet to always be located 15 cm above the manure surface. The air inlet included a baffle to direct the air radially in all horizontal directions so that the incoming air did not blow directly onto the manure surface. The eight reactors were placed in a 4.5 m x 2.7 m insulated and environmentally controlled walk-in test chamber, which was maintained at about 20°C.

An air compressor provided ventilation air to the reactors continuously except during manure addition and additive application (Figure 2). Pressurized air was filtered; and the pressure was reduced and stabilized after going through two pressure regulators that were connected in series. An air supply manifold (M_a, Figure 2) distributed air equally to each reactor at 7.0 L min^{-1} using 0.84-mm diameter stainless steel precision orifices. An airflow rate of 7.0 L min^{-1} was selected to simulate similar air exchange as in layer hen houses during cold weather.

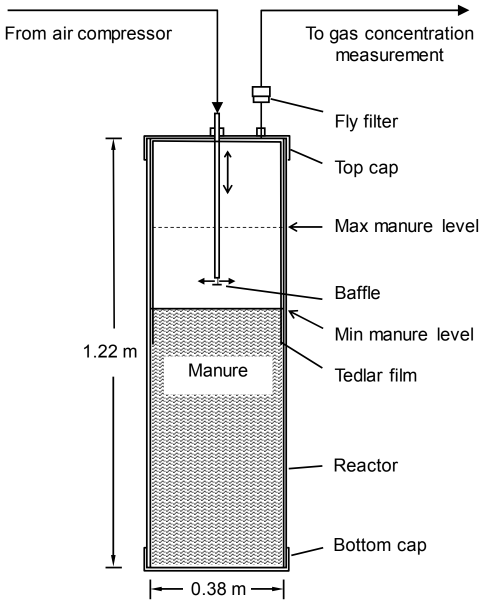

Figure 1: The reactor. The "top cap" was removed during manure addition, additive spray, and reactor empting. The position of the air supply pipe was adjustable (indicated with the vertical double-ended arrow).

A Teflon® filter holder with a foam dust filter was installed in each reactor to remove manure flies from exhaust air. An air sampling setup, constructed for automatic sequential sampling, allowed exhaust air from a selected reactor or the fresh air from M_a to pass through a solenoid to a ported Teflon sampling manifold (M_s, Figure 2). The exhaust air from each reactor flowed under pressure through a 6-m long Teflon tube to a computer-controlled array of nine 3-way Teflon-lined solenoids (S_0 to S_8, Figure 2) in the instrumentation room, which was immediately adjacent to the test chamber.

The common port of the solenoid was connected to the reactor exhaust air. The normally closed port was connected to the air exhaust located under an exhaust hood. The reactor exhaust air was discharged to the outdoors when the airflow rate and gas concentrations of that reactor were not being measured. The normally-open port of the solenoid was connected to the sampling manifold, M_s. The air flowing directly from the air supply manifold, controlled by the solenoid S_0, was also sampled to provide a blank air check during each sampling cycle.

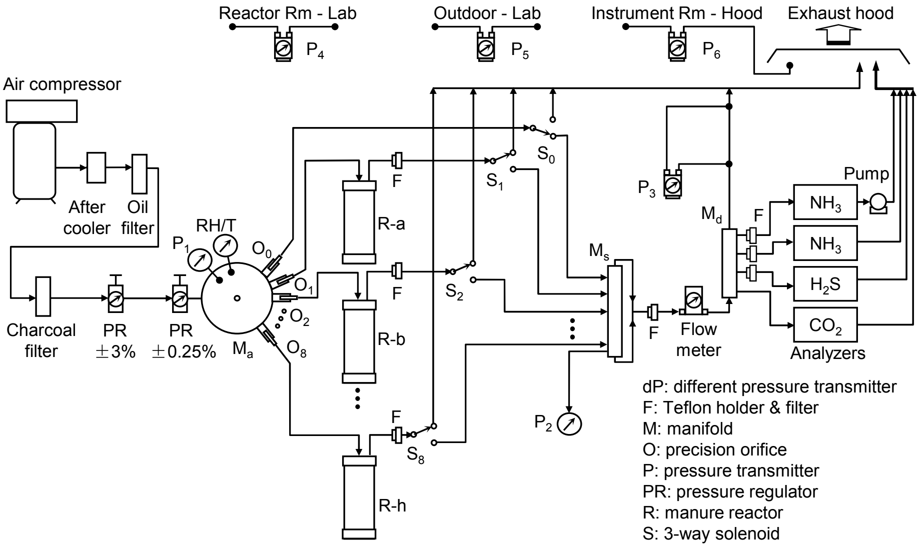

Figure 2: Laboratory setup airflow diagram. Three of the gas analyzers had internal filters and/or pumps.

Manure and manure addition

Layer hen manure was collected from a commercial high-rise layer hen house in Ohio state by the laboratory study sponsor. The house (House 1) was 201 m (L) by 21 m (W) and had a capacity of 170,000 layer hens. Hen manure dropped in the manure pit onto eight 185-m long manure windrows. The manure for the test was taken from the surface to the core of two manure windrows that had accumulated for about six months. The manure was collected in the early morning of day -1 before the study began, sealed into plastic bags and placed into cardboard boxes, and delivered to the testing lab on the same day.

The initial reactor filling was conducted on day zero (0). The boxes of manure, each weighing between 12.7 and 20.0 kg, were randomly selected for filling into each reactor until the height of manure reached 66 cm. The average quantity of manure added was 45.1 kg per reactor and the average manure density was 596 g L^{-1}.

Bags containing 3.4 kg manure each were also prepared on day 0 for subsequent weekly additions and the bagged manure was kept frozen. To simulate field conditions, 5 cm of thawed manure (one bag of 3.4 kg) was added to each reactor every week during the first three weeks. Due to insufficient quantity of source manure collected on day -1, more manure was collected on day 27 from another house (House 2) at the same farm for the fourth addition on day 28. The manure collected on day 27 was not kept frozen before being added into the reactors.

Three samples were taken from the source manure on day 0 before initial filling. Samples of the day 28 source manure were not available due to a test error. To make up the lost data, one manure sample was taken from the top manure (manure added on day 28) in each reactor on day 38 immediately after the reactor top lid was opened. The manure in each reactor was then emptied into a tub and mixed. Three manure samples were taken from the mixture for each reactor. The manure samples were analyzed for pH, and concentrations of moisture, total nitrogen, and ammonium in the Animal Sciences Waste Management Laboratory at Purdue University.

Additive preparation and application

The manure additive was supplied by the laboratory study sponsor. Eco-Cure Inc. provided instructions about the additive preparation and application dosage directly to the research team of this study before and during the study. To prepare the additive that was originally in solid form, 15 g of additive were submerged into 2 L of 35°C water, which contained less than 0.5 ppm chlorine and had a pH of 7.02, for at least five hours to obtain a solution that looked similar to brown tea.

The additive solution applied to each treated reactor was 35 mL for the initial application and 15 mL for each of the weekly applications. Nothing was applied to the control reactors. The solution was sprayed onto the manure surface inside the treated reactors as uniformly as possible using a hand pump spray, which consistently sprayed 2.5 mL of liquid every squeeze of the pump. The weekly application started after the manure addition operation, which took about two hours to complete.

Gas concentration measurement

The sample air stream from each of the eight reactors was measured sequentially for 10 min before switching to another reactor. The background air sample flowing directly from the air supply manifold was sampled for 30 min. It required 110 min (1 h and 50 min) to scan through the background air and the eight reactors. Slightly more than six measurements were obtained daily for each of these eight reactor during typical measurement days, excluding days for weekly manure addition and system maintenance.

At the beginning of the study, NH_3 concentration in sample air was measured with an ammonia analyzer (Model 17C, Thermal Environmental Instruments, Inc., Franklin, MA, USA), which first converted NH_3 into nitric oxide (NO) then measured the NO concentration with a chemiluminescence detector. The analyzer had a lower detectable limit of 1 part per billion (ppb). Its 24-hour span drift was 1% of full scale. The NH_3 analyzer was set at 0-200 ppm measurement range. However, the analyzer was pegged during the first day of measurement with unexpectedly high NH_3 concentrations (>200 ppm) in the reactor exhaust air. A Chillgard IR Refrigerant Leak Detection System (Mine Safety Appliances Company, Pittsburgh, PA, USA) was therefore installed on day 2. This instrument was based on the photoacoustic infrared sensing technology. Its display resolution was 1 ppm with a measurement range of 0 to 1000 ppm and response time was 90% of a step-change in 70 seconds. Its stability was ± 1 ppm in 0–100 ppm measurement and ± 10% of reading in 100–1000 ppm measurement.

A photoacoustic infrared carbon dioxide (CO_2) analyzer (Mine Safety Appliances, Pittsburgh, PA, USA) was installed and used throughout the study to measure CO_2 concentrations. Its normal measurement range was 0–5000 ppm and was extended to 0–10,000 ppm for this study by adjusting its sensitivity as suggested by the instrument manufacturer. The precision of the analyzer was ± 100 ppm. Carbon dioxide concentration was initially used as an indicator to compare with the NH_3 concentration for research quality control. For example, if both CO_2 and NH_3 were not detected, it could be an indication of sampling system failure.

A hydrogen sulfide analyzer (Model 45C, TEI, Franklin, MA, USA) was also installed for H_2S measurement (Figure 2 **錯誤! 找不到參照來源。**). The analyzer detection limit was 2.0 ppb H_2S. Its precision was 1% of the reading or 1 ppb.

All the gas analyzers were calibrated or zero/span checked prior to and after the study, and at least weekly during the study using certified zero air, and NH_3, CO_2, and H_2S calibration gases.

Airflow rate, temperature, relative humidity, and pressure measurement

A mass-flow meter with 0–10 L min^{-1} measurement range (Model 50S-10, McMillan, Georgetown, TX, USA) was used to measure the airflow rate from each reactor when the gas concentrations of that reactor were being measured.

Air temperature in the reactor room was monitored in four locations with type T thermocouples. An electronic relative humidity and temperature probe (Humitter 50 YC, Vaisala, Woburn, MA, USA) was used inside the air supply manifold (M_a) to monitor relative humidity and temperature.

Six pressure sensors were installed to monitor the test system. The first sensor measured the pressure inside manifold M_a. The second monitored the pressure in the air sampling manifold (M_s). The third monitored the pressure at the exhaust air of the distribution manifold (M_d) to ensure sufficient air supply during analyzer calibration (Figure 2). The three other sensors monitored static pressures of the exhaust hood, the reactor room, and the instrumentation room, respectively.

Data acquisition and control

The data acquisition and control (DAC) system consisted of a personal computer and

FieldPoint DAC hardware (National Instruments, Austin, TX, USA). The DAC program for this study was written in LabVIEW (National Instruments). Measurement data were sampled every second and averaged and recorded every minute. The DAC program controlled the solenoids for automatic air sampling (Ni and Heber, 2010).

Odor evaluation

To evaluate the additive effectiveness on odor reduction and assess the performance claim that the sponsor received from the additive vendor, the odor intensities of the reactor exhaust air were evaluated by four trained odor panelists before and after the day-14 additive application. Each panelist directly sniffed the reactor exhaust air, and recorded an odor intensity based on comparison with a reference scale of n-butanol solutions (ASTM Committee E-18, 1992). The concentrations of n-butanol in water of the 5-point scale reference were 250, 750, 2250, 6750, and 20,250 ppm for levels 1 to 5, respectively. The panelists were allowed to score at 0.5 level increment. The odor intensities of the control and treated reactors were sniffed before and after application of the additive. This comparison of odor intensities was also used to evaluate the longer term (7 d) effectiveness of two previous additive applications on days 0 and 7.

Open-headspace tests

Open-headspace tests were conducted to simulate commercial demonstrations of the additive product and to corroborate the results of the reactor study. Manure was tested twice using a 38-cm diameter and 8-cm deep pan on days 21 and 28. Layer hen manure taken from the frozen supply of source manure and thoroughly mixed was placed in the pan. An inverted funnel (10-cm diameter opening) was held 1.5-cm above the surface of the manure in the pan to collect a continuous air sample. The funnel was connected to the 17C NH_3 analyzer and the CO_2 analyzer for continuous measurement. The vacuum pumps of the analyzers drew sample air continuously from the funnel at about 2 L min^{-1}

On the day 21 test, 17 mL of additive solution was sprayed directly onto the surface of 1.1 kg layer hen manure in the pan, which was placed on the floor of the laboratory. Gas concentrations were compared before and after the spray. The test was repeated on the same day with 2.3 kg of manure. Additive solution (15 mL) was sprayed once onto the manure to compare their effects. The measurement continued overnight for a total of 13 h.

On the day 28 test, 3.1 kg of layer hen manure was used in the pan, which was placed inside a 40 cm (H) x 43 cm (W) x 66 cm (L) plastic box to reduce the effect of room air circulation on the gas release from manure. Gas measurements were made continuously for 25 h; and 15 mL of additive solution was sprayed onto the manure 3 hours after the measurement started.

Data processing and analysis

In data processing, only the last 3 min of gas concentration data during the 10 min or 30 min measurement were used. The first 7 or 27 min data were ignored because these were the time that the measurement system needed to equilibrate after switching from one sampling location to another. Gas release rate was calculated by multiplying the airflow rate by the gas concentration difference between the reactor exhaust air and the reactor inlet air, after converting from volumetric concentration (ppb or ppm) to mass concentration ($\mu g\ m^{-3}$). Gas release flux was calculated by dividing the release rate by 0.114 m^2 of the reactor top surface (38-cm diameter), not the actual poultry manure surface areas exposed to the air. The actual manure surface was rough and irregular and was technically impossible to determine in this study.

Several means were defined in this study depending on the coverage of time duration (4 h, 1 day, and 38 days) and number of reactors (1 reactor and 4-reactor group). For example, a “group daily mean” was calculated for a 4-reactor group with 1 day of data; and an “average reactor mean” was calculated for a single reactor from 38 days of data (Table 2).

Table 2: Means defined and used in the data analysis.

Time coverage	Reactor coverage		
	Individual reactor	4-reactor group	8 reactors
4-h sample	Reactor sample	Group sample mean	8-reactor sample mean
1 day	Reactor daily mean	Group daily mean	8-reactor daily mean
38 days	Average reactor mean	Average group mean	Average 8-reactor mean

Statistical t-Test (two-tailed unequal variances) was performed to compare the analysis results of manure samples taken from the treated and control reactors. It was also used to compare the manure odor intensities and the group daily means gas release rates between the treated and control groups. Single factor ANOVA was used to compare the differences between the eight reactors using reactor daily means.

RESULTS AND DISCUSSION

Manure characteristics

Results of manure analysis showed that the pH of three types of manure samples (i.e., source manure from hen House 1 sampled on day 0, reactor top manure from House 2 that was added on day 28 and sampled on day 38, and reactor mixed manure sampled on day 38) was very close and ranged from 8.69 to 8.79 (Table 3). Manure from House 2 had apparently higher concentrations of moisture, total N, and ammonium than that from House 1.

However, no statistical differences were observed between the control reactors and the treated reactors for all the analyzed variables (pH, moisture, total N, and ammonium) in reactor top manure and mixed manure sampled on day 38 (P > 0.30) (Table 3). This demonstrated that no effects of the Eco-Cure application on manure characteristics were observed.

Table 3: Mean ± standard deviation (STD) of manure analysis results.

Manure sample and T-Test	Sample, n	Mean ± STD			
		pH	Moisture, %	Total N, ppm	NH_4^+, ppm
Source manure from House 1					
Control and treated reactors on day 0	3	8.79 ±	33.85 ± 2.29	18,056 ± 912	5296 ±

		0.06			652
Top manure from House 2					
Control reactors on day 38	4	8.73 ± 0.08	43.02 ± 5.28	27,541 ± 3078	8860 ± 740
Treated reactors on day 38 [*]	3	8.78 ± 0.08	40.53 ± 2.69	25,247 ± 4198	8126 ± 653
Control vs. treated (P value)		0.51	0.52	0.55	0.30
Mixed manure from Houses 1 and 2					
Control reactors on day 38	12	8.69 ± 0.07	37.03 ± 2.64	19,481 ± 1531	6497 ± 607
Treated reactors on day 38	12	8.71 ± 0.08	37.5 ± 3.31	19,162 ± 1882	6848 ± 943
Control vs. treated (P value)		0.66	0.72	0.67	0.31

Note: [*] Day 38 R-g top manure was not available due to a sample error.

Reactor gas concentration and release

Data overview

Between 214 and 223 group sample means of NH_3 and CO_2 concentrations and calculated releases were obtained for the control and treated groups (Table 4). Hydrogen sulfide concentrations were below the detection limit of the gas analyzer. This agreed with other field studies, which demonstrated that H_2S concentrations and emissions at high-rise layer hen houses were very low compared with commercial pig buildings (Ni et al., 2012; 2017). Therefore, H_2S concentrations and releases between control and treated reactors could not be compared in this study.

Table 4: Averaged group mean (AGM) ± standard deviation (STD) of ammonia and carbon dioxide concentrations and releases from the control and treated reactors.

	Control group (R-a to R-d)		Treated group (R-e to R-h)	
Parameters	AGM ± STD	GSM, n	AGM ± STD	GSM, n
NH_3 concentration	196 ± 161 ppm	222	229 ± 143 ppm	223
NH_3 release rate	17.5 ± 14.3 $\mu g\ s^{-1}$	222	20.1 ± 12.6 $\mu g\ s^{-1}$	223
NH_3 release flux	153.7 ± 125.3 $\mu g\ s^{-1}\ m^{-2}$	222	176.6 ± 110.4 $\mu g\ s^{-1}\ m^{-2}$	223
CO_2 concentration	5288 ± 740 ppm	214	5559 ± 1103 ppm	215
CO_2 release rate	1091 ± 149 $\mu g\ s^{-1}$	214	1143 ± 217 $\mu g\ s^{-1}$	215
CO_2 release flux	9566 ± 1310 $\mu g\ s^{-1}\ m^{-2}$	214	10024 ± 1904 $\mu g\ s^{-1}\ m^{-2}$	215

Note: Group sample means (GSM) were used to calculate 38 group daily means, which were then used to calculate averaged group means.

Effect of additive on ammonia and carbon dioxide concentration and release

Compared with the control group, the treated group NH_3 had about 16.8% higher average concentration and 14.9% higher average release rate (Table 4). However, statistically there were no significant differences for both NH_3 concentrations ($P = 0.35$) and releases ($P = 0.41$). The additive was therefore not effective in reducing NH_3 release from layer hen manure in this study.

The treated group CO_2 had about 5.1% higher average concentration and 4.8% higher average release rate compared with the control group (Table 4). However, these differences were not statistically significant ($P > 0.21$ for CO_2 concentration and $P > 0.23$ for CO_2 release rate). Therefore, no effects of the additive on CO_2 from manure were observed.

Temporal variations of ammonia and carbon dioxide releases

The daily mean NH_3 releases increased substantially after each weekly manure addition, despite the immediate additive application, followed by a gradual decrease until the subsequent addition (Figure 3, top). Nevertheless, the peaks that occurred after the first three additions of stored manure on days 7, 14 and 21 were much lower than those after the last addition of one-day old fresh manure on day 28, which produced peaks that were more than 3.5 times as high as the previous additions. The day 28 manure from House 2 had higher moisture, total N, and ammonium concentrations compared with the day 0 source manure from House 1 (Table 3), demonstrating that different poultry manure could have very different NH_3 release potentials. Consequently, the NH_3 release rate after the day-28 manure addition and additive application was 1330% as high as before the addition, demonstrating that fresher manure with higher moisture concentrations had substantially higher NH_3 release potentials. However, no reductions in NH_3 concentrations or releases were observed immediately after each additive spray application in the reactors. Therefore, this additive did not exhibit an immediate effect on NH_3 release from layer hen manure as claimed by the manufacturer.

Similar behaviors of CO_2 release from the manure were also observed (Figure 3, bottom). The CO_2 releases increased after the manure additions and additive applications, and decreased gradually thereafter, showing the same fluctuation patterns as NH_3. Although the increase in CO_2 release after the fourth weekly addition with manure of higher moisture concentration was much more intense relative to the three previous additions, it was not as high as that of the NH_3 release. However, additive application did not noticeably alter the CO_2 release patterns for the treated reactors compared with the control reactors.

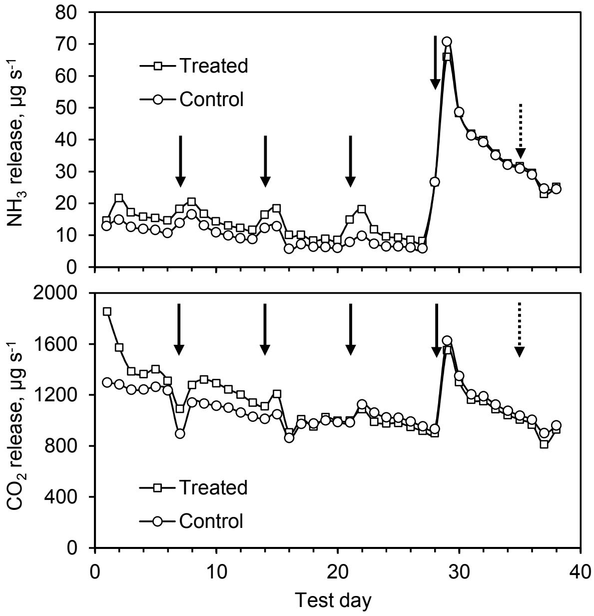

Figure 3. Group daily mean release rates of ammonia (top) and carbon dioxide (bottom) from the treated and control groups. Solid arrows: manure additions and additive applications. Dotted arrows: additive application only.

Ammonia and carbon dioxide release among individual reactors

The average reactor mean NH_3 releases from the manure in the eight individual reactors ranged from 15.3 µg s^{-1} (R-a) to 23.2 µg s^{-1} (R-f) (Figure 4, top). According to the ANOVA analysis results, no significant differences were found for NH_3 releases between the eight reactors ($P = 0.20$). The variations in NH_3 releases cannot be obviously related to the effect of the additive, but most possibly to the variations of the manure sources, which were randomly assigned to each reactor (Table 3). Similar variations in NH_3 concentrations among different reactors was observed in previous studies using swine manure, dairy manure, beef manure, and municipal sludge (Tengman et al., 2001; Dunn, 2004; Dai et al., 2015).

The average reactor mean CO_2 releases from the manure in individual reactors ranged from 982 µg s^{-1} (R-d) to 1340 µg s^{-1} (R-f) (Figure 4, bottom). Compared with NH_3, the variations in CO_2 releases from manure among different reactors were more profound. The ANOVA analysis results showed significant differences for CO_2 releases between the eight individual reactors ($P < 0.001$). However, these CO_2 release variations were randomly distributed and could not be related to the effects of additive applications.

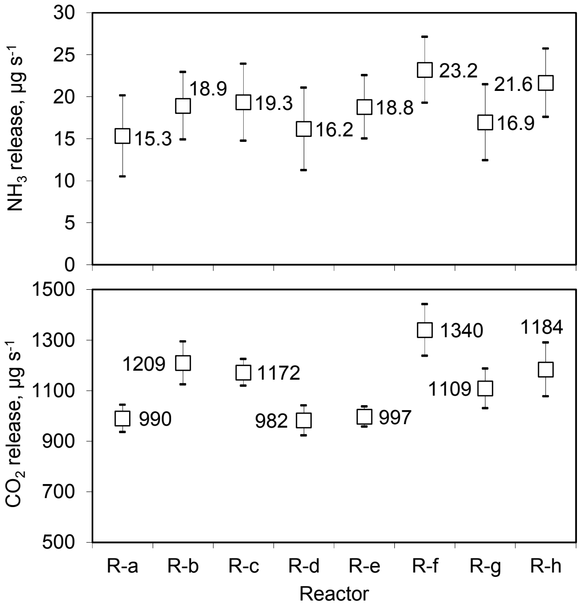

Figure 4. Average reactor mean ± 95% confidence interval of ammonia (top) and carbon dioxide (bottom) releases in the control reactors (R-a to R-d) and treated reactors (R-e to R-h).

Odor intensity

The group mean odor intensities of the reactor exhaust air were 3.4 ± 0.3 and 3.5 ± 0.3 for the control and treated groups, respectively, before the day-14 additive spray using the 5-point n-butanol reference scale. No effect on odor intensity reduction by the additive applications on days 0 and 7 was demonstrated ($P > 0.71$). The odor intensities of the treated reactors were 3.5 ± 0.3 and 3.4 ± 0.3 before and after the additive spray, respectively. No statistically significant difference was observed ($P > 0.77$) to reject the null hypothesis that the additive did not reduce odor intensities in the air from layer hen manure based on the odor sniffing test.

Open-headspace gas release

During the day 21 open-headspace test, concentrations of NH_3 and CO_2 above the manure surface gradually decreased after the monitoring began. However, NH_3 concentrations started to increase 90 min after the additive spray and stayed at about 55 ppm for 3 h before it decreased again and remained at about 10 ppm overnight. It was noticed that air movement in the lab due to research activities may have contributed to the concentration variations. Nevertheless, an immediate elimination of NH_3 after additive spray as claimed for the additive product was not observed.

The day 28–29 open-headspace test confirmed the results of the day 21 test that the additive spray at 15:45 did not reduce NH_3 release (Figure 5). The gas concentrations in this test were more stable than the day 21 test and NH_3 remained at about 30 ppm throughout the test due to the use of the plastic box, from which the released gases flowed out of the box by convection. Concentrations of both NH_3 and CO_2 suddenly increased to 137 ppm and 1450 ppm, respectively, when the top of the box was briefly covered for 1 min, manifesting high release rates of the gases from manure (Figure 5).

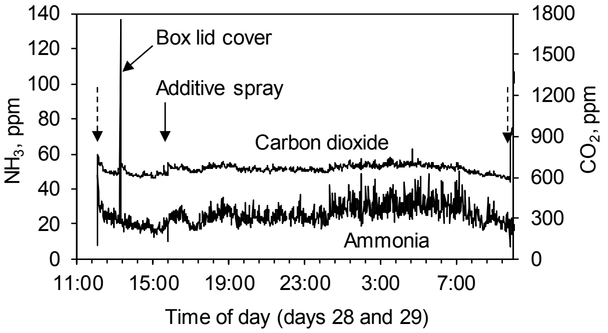

Figure 5. Results of open-headspace test on days 28 and 29. The left and right dashed arrows indicate the start and end of the test, respectively.

Comparison between laboratory simulation and field condition

Ventilation

The ventilation flux on manure surface in this study was 64 L min^{-1} m^{-2}. The measured minimum and mean ventilation in commercial layer hen houses were 295 and 2420 L min^{-1} m^{-2}, respectively (Heber et al., 2005). The volumetric air exchange rate in the reactor headspace varied from 6.7 to 10.4 air changes per hour (ach) compared with the minimum and maximum layer hen house ventilation rate of 4.7 and 53 ach, respectively. Therefore, whereas the volumetric airflow rate in the study simulated winter ventilation rates in the layer hen house, surface based ventilation rate was generally lower than in the layer hen houses. The surface to volume ratio in the reactor ranged from 1.8 to 2.8 m^2 per m^3 compared with about 0.20 m^2 per m^3 in the layer hen house. Thus surface to volume ratio was about 8–13 times higher in the reactors than in the houses. However, the higher concentrations of NH_3 in the reactors were mainly due to the relatively lower surface-specific ventilation compared with the layer hen house situations, and most of the NH_3 release is expected to be from fresh manure on the surface of the manure windrows.

Ammonia concentration and release

The AGM NH_3 concentrations in the reactor exhaust air were much higher than that measured in the exhaust air of the commercial layer hen farm, from which the reactor manure was obtained. The NH_3 concentrations measured in two of the 250,000-hen high-rise layer hen houses at the farm averaged 34 ppm in a 380-d long continuous measurement campaign with the maximum daily average of 108 ppm (Heber et al., 2005). However, the average reactor mean NH_3 concentrations were close to the maximum daily mean NH_3 concentrations, which were 176 and 182 ppm, in two other reported high-rise layer hen houses (Ni et al., 2012), showing at least some similarities between the laboratory and field conditions.

The average 8-reactor mean of NH_3 release flux was 164 μg s^{-1} m^{-2}, which was only about 26% of the 622 μg s^{-1} m^{-2} of manure pit floor area in the layer hen houses (Heber et al., 2005). Field data, however, included releases from the cage area inside the layer hen houses. The inverted V-shaped manure windrows in high-rise layer hen houses also had much large manure surface areas than the pit floor area. Additionally, the layer hen houses had fresher manure that dropped frequently onto the top of manure piles and ventilation rates that varied diurnally and seasonally compared with the laboratory setup. Therefore, higher NH_3 release flux per pit floor area in the layer hen houses could be expected.

CONCLUSIONS

The following conclusions were obtained in this study:

1. Applications of Eco-Cure in four laboratory reactors did not alter manure pH, moisture, total nitrogen, and ammonium in the treated manure compared with manure in four control reactors.

2. Reductions in NH_3 releases from layer hen manure after the additive application were not observed.

3. No effects of the additive on reducing odor intensity of layer hen manure were observed by the odor panel.

4. Spraying the additive solution onto manure surface in the open-headspace did not demonstrate immediate reduction on NH_3 and CO_2 concentrations near the manure surface.

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Figure Captions

Figure 1: The reactor. The “top cap” was removed during manure addition, additive spray, and reactor empting. The position of the air supply pipe was adjustable (indicated with the vertical double-ended arrow).

Figure 2: Laboratory setup airflow diagram. Three of the gas analyzers had internal filters and/or pumps.

Figure 3. Group daily mean release rates of ammonia (top) and carbon dioxide (bottom) from the treated and control groups. Solid arrows: manure additions and additive applications. Dotted arrows: additive application only.

Figure 4. Average reactor mean ± 95% confidence interval of ammonia release (top) and carbon dioxide release (bottom) from the control reactors (R-a to R-d) and treated reactors (R-e to R-h).

Figure 5. Results of open-headspace test on days 28 and 29. The left and right dashed arrows indicate the start and end of the test, respectively.